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Anomalous piezoelectric effects found in the laboratory and reconstructed by numerical simulation

Krzysztof P. Teisseyre
Institute of Geophysics, Polish Academy of Science, Warszawa, Poland

Abstract
Various rocks and minerals, which are not piezoelectric in the common sense, exhibit transient electric polarization in response to sudden changes in stress load. This anomalous piezoelectric effect differs from the regular, static piezoelectric response, in which electric charges appear as a result of crystal lattice deformation. The anomalous piezoelectricity is dynamic decaying in a few seconds or a few tens of seconds. However, in some materials different polarization properties are discovered. To explain certain aspects of the polarization signal increase and decay, some complicated mechanisms of electric charge generation and relaxation need to be assumed in their number – concurrence of two or three relaxation processes. The hypothetical mechanisms are only mentioned, as the purpose of this work is to construct numerical models, behaving like the rocks investigated. Examples of experimental plots are shown together with the results of the numerical simulation of these experiments.

Key words *anomalous piezoelectric effect – transient electric polarization – electric properties of rocks*

1. Laboratory experiments with rock samples subjected to a change in load

The laboratory research was done by Vassilios Hadjicontis and Claire Mavromatou, in the Department of Physics, University of Athens. Samples of various rocks held initially under a certain steady load, were subjected to a quick increase in load, in some cases followed by a decrease after some time to almost the initial level. The charge detecting-recording system contains an electrode adjacent to the sample wall (at a distance of 5 mm), the load sensor positioned below the sample and a digital recording apparatus with oscilloscope and printer.

Either the plot of applied load and curve of electric signal *versus* time, or the plot of the load time-derivative and again the plot of the generated electric signal were seen on the screen.

A detailed description of the experimental setup was published by Hadjicontis and Mavromatou (1995). These authors suggest that the obtained curves of electric signal are proportional to the time-derivative of load (pressure) acting on the sample. The present work checks this hypothesis by means of numerical analysis and suitable simulating algorithms.

Mailing address: Dr. Krzysztof P. Teisseyre, Institute of Geophysics, Polish Academy of Science, Księcia Janusza 64, 01-452 Warszawa, Poland; e-mail: kt@igf.edu.pl

2. Modelling of the signal components generation and relaxation

The time derivative of load was, for this modelling, read from experimental curves and written as the input data (for future simulations, use of data in digital form is planned). Certain formulae for the simulations were developed and tested, corresponding to some models of electric signal generation and relaxation in the rock. The stimulus – actual value of time derivative of load (dp/dt), multiplied by proportionality coefficient K, contributes to the state of polarization at a given stage, and indirectly also at following stages. The indirect effect diminishes exponentially with time. In other words, the polarization process may create at each stage some element of electric response and this element immediately starts to decay, according to exponential routine. Therefore, the electrical signal at a given stage i results from the value of actual stimulus and the sum of previous stages influence

$$V_i = \sum_{n=1}^{i} \left(\frac{dp}{dt} \right)_n K \exp\left(-\frac{i-n}{l} \right)$$

where V is the generated electrical signal; K - proportionality coefficients; l - relaxation coefficient.

In order to simulate the experimental results, some complications are added to this method. The most important is: the energy given by each stimulus (dp/dt) is divided into two or three parts: a quickly-decaying electric polarization process; a medium speed process and a long-relaxation one; the differences lie in the values of relaxation coefficient l.

A multiple mechanism of relaxation is also proposed by Varotsos *et al.* (2001), who explain the Greek limestone and Polish peridotite behaviour (in similar tests) by concurrence of three relaxation processes: one fast and two long relaxation ones. They also suggest that the deformation-induced charge flow mechanism might be the appropriate generation mechanism for the Seismic Electric Signals.

Rock samples, which are at first sight very similar, respond in the experiments slightly differently. To reconstruct the course of their polarization and its decay, different coefficients are assumed. Moreover, the same sample may react in various way to the *rise* of load and to *decrease* – partial removing of the force. This points to the micro-cracks and dislocation arrays mediation in the process of charge separation and migration.

In some cases of simulation, the so-called «opposite components» are added to the signal. These are caused by *stopping the load increase* and to explain their existence, a kind of rebound processes within the sample is postulated. The decrease of direct response should be abrupt enough to act as a meta-stimulus on the material, that is to create a component of the electric signal bearing the opposite sign. Such phenomena may be explained if one assumes the mediation of dislocations and micro-crack *movements* in the processes of charge separation and summation.

Only in a few cases does the opposite components pile give an effect of opposite bay-bay-like flexion of the signal curve below the initial level. One of such cases is included here. Such defined opposite components depend on the proportionality coefficient K mentioned previously, and on the additional coefficient K_{op}. Although it may be expected that K_{op} should not be greater than 1, for some cases, a greater value of this coefficient must be taken, in order to obtain similarity with the experimental results. Opposite bays phenomena, as seen here in fig. 2, are hard to explain in another way.

Besides, at the time of response generation to any stimulus or meta-stimulus, this direct response is normalized in such a way that it cannot exceed a certain value, common for all considered cases. Influence of this normalization is mild.

It must be pointed out that physical values of stimulus, in dp/dt and the simulated signal in mV, are calculated *ex post*; simulation *de facto* consisted of transforming one synthetic plot into another. Nevertheless, the physical values of K-coefficients were *ex post* calculated.

3. Three examples of experiment and simulation results

Here we compare the laboratory data and those obtained by numerical simulation; in presented figures the upper part shows the load acting on the sample (one division corresponds to 100 kG), below – the recorded electric signals and the load time-derivatives, the lower part represents simulation results.

In the experimental diagrams, the horizontal axis shows time in seconds – one division on horizontal axis corresponds respectively in case (1) to 5 s, in other cases to 2 s.

1) Volcanic tuff sample (fig. 1). Two episodes of increase in the load; the second caused a new signal peak before the first vanished completely. Initial load = 330 kG, maximal load ~ 800 kG. On the plot of the observed electric signal, one division in the vertical direction

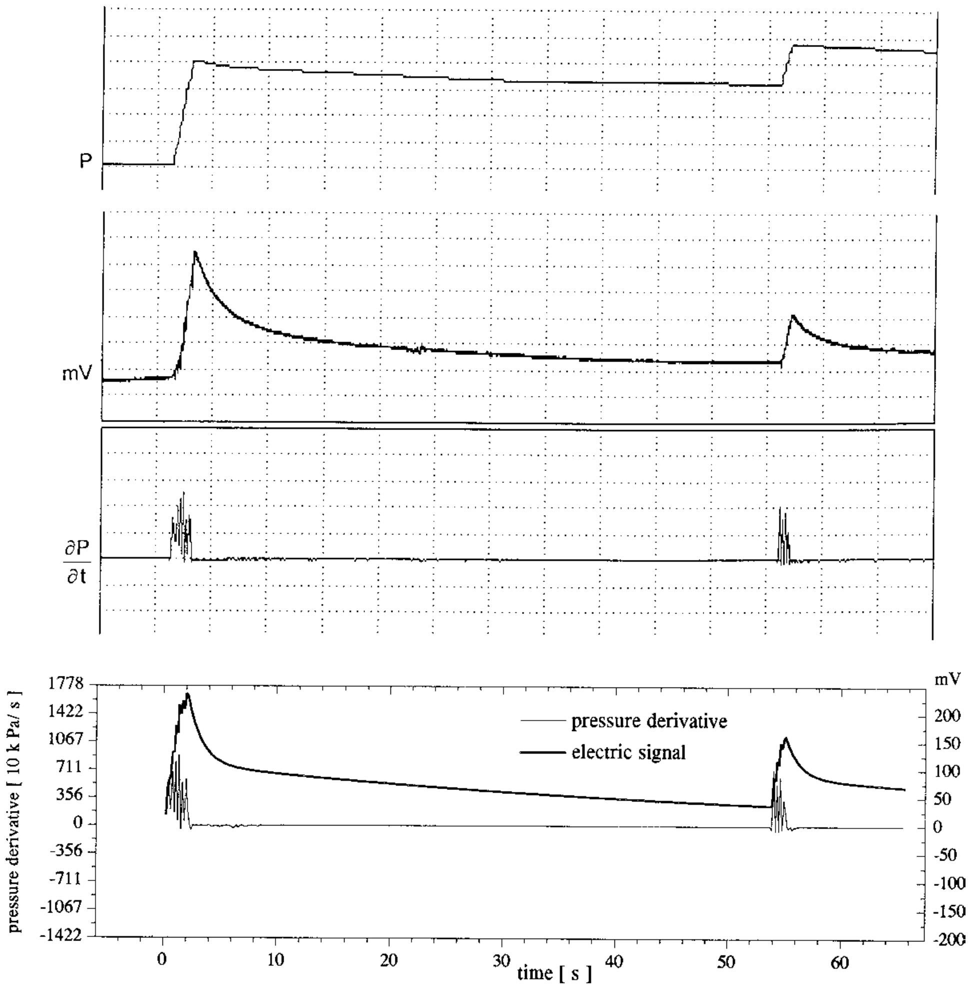

Fig. 1. Experiment with sample of volcanic tuff: the load, electric signal, load time-derivative and the simulation of electric signal curve.

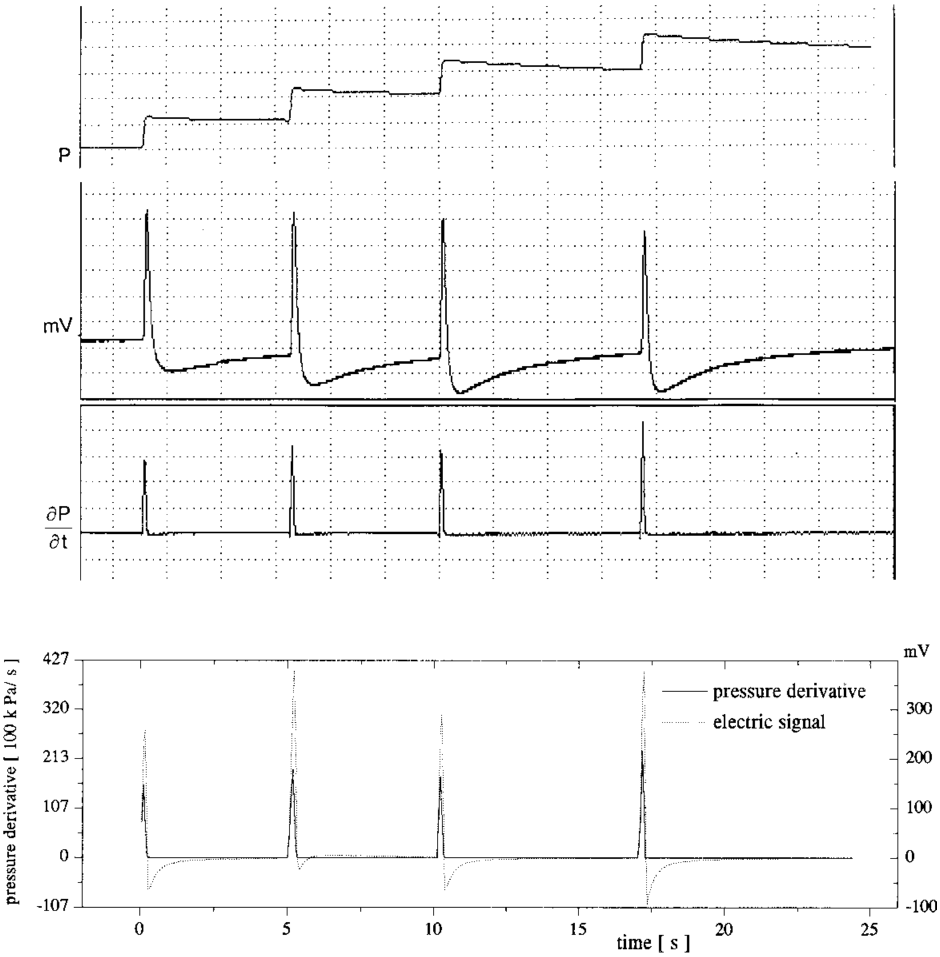

Fig. 2. Experiment with sample of limestone: the load, electric signal, load time-derivative and the simulation of electric signal curve.

corresponds to 50 mV. The calculated proportionality coefficient K is $7.2 \cdot 10^{-7}$ mV s/Pa; in the simulation: $K = 0.51$. Proportion of quickly decreasing part to whole new signal component is at first 70%, of slowly decreasing part – 30%; respective l – coefficients are 8 and 320.

2) Jurassic limestone from Poland (fig. 2). Four consecutive strikes were applied to the sample. Initial load = 330 kG, maximum ~ 750 kG. On the plot of observed electric signal, one division in the vertical denotes 100 mV. The calculated proportionality coefficient K is $1 \cdot 10^{-7}$ mV s/Pa; in the simulation: $K = 1.1$; proportion of quickly decreasing part to new signal is at first 53%, for middle quick – 29%, remaining 18% starts the slowest, long-lasting part; coefficients l are 4, 10 and 50. Additional proportionality coefficient for opposite components K_{op} is very big: 2.43.

3) Another experiment on the jurassic limestone from Poland (fig. 3). Episode of the load increase, stationary phase and the phase of

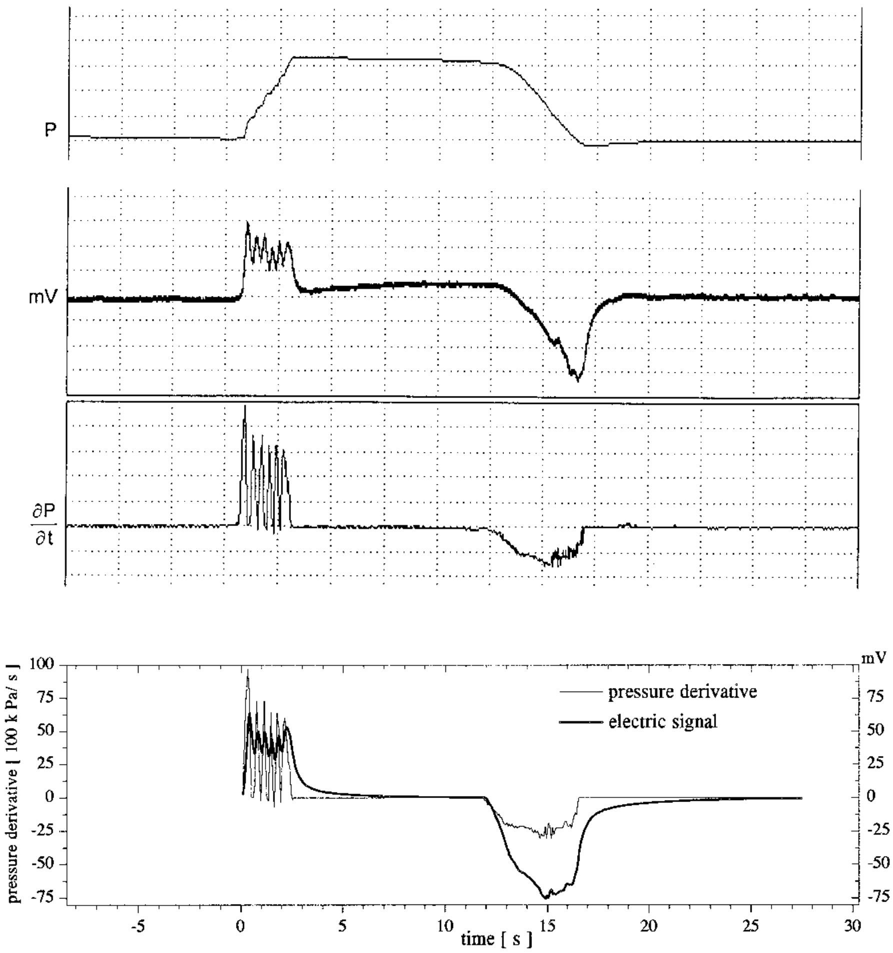

Fig. 3. Another experiment with the limestone: the load, electric signal, load time-derivative and the simulation of electric signal curve.

load decrease. Initial load = 310 kG, maximal ~ 633 kG. On the plot of registered electric signal, one division denotes 20 mV. The calculated proportionality coefficient K is for load increase phase $2.35 \cdot 10^{-6}$ mV s/Pa, and for the phase of load decrease: $6.8 \cdot 10^{-6}$ mV s/Pa; in the simulation: $K = 0.235$ and for the load decrease $K = 0.68$. Proportion of quickly decreasing part to whole new signal component is at first 82%, of middle one – 15%, slowest one has initially 3%. Respective relaxation coefficients l are 4, 10 and 50. Additional proportionality coefficient for opposite components K_{op} is 0.13.

4. Discussion

We present some examples of the electric responses to stress load on rocks to emphasize their complex response mechanisms. The current theories of piezoelectricity or piezoelectric gradient, include usually only the direct response and, additionally, its relaxation. Numerical simulations undertaken in the presented project show that the induced electric potential response to stress load has a complex structure and that its relaxation includes at least a slow and a rapid mechanism.

For the volcanic tuff, a simple model appears to be satisfactory: a twin-component signal summation and relaxation. On the other hand, the response of some rock materials may be satisfactorily modelled only with the assumption of a larger number of polarization processes occurring simultaneously, each one decaying with appropriate schedule, depending on the l coefficient of the presented formula. To achieve a better agreement with the experiments on some rocks including limestone, a hypothesis of opposite components is formulated. In the presented case (2), the opposite components increase is ruled by a greater coefficient of proportionality K than that of the main component. Probably some peculiar structure of the sample is responsible for this effect and it cannot be excluded that in other parts of the sample, a little further away from the electrode, the signal behaviour may be different.

Satisfactory agreement between experiment and its reconstruction was not obtained in some cases (see fig. 2) and this suggests that more components are in fact involved. It cannot be stated that all components necessary to explain the complex behaviour of some rocks are already discovered, experiments as well as modelling are underway. Examples of more complex modelling have recently been published by Teisseyre *et al*. (2001).

Transient electric polarization was also detected in various rocks subjected to high loads, close to brittle fracture (Enomoto *et al*., 1994). In experiments conducted in Athens such signals were also observed close to the sample fracturing (Hadjicontis and Mavromatou, personal communication). Production and propagation of electric signals under variable load are important phenomena both in the physics of rocks and in the search for various detectable earthquake precursors (Enomoto *et al*., 1994; Varotsos *et al*., 2001).

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